Variability in the Spreading Pathways of the Red Sea and Persian Gulf Outflows

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LONG-TERM GOAL

Our long-range objective is to understand the mechanisms that affect the spreading and mixing of marginal sea outflows. The Red Sea and Persian Gulf outflows flow over relatively shallow sills at low latitude into a strongly stratified oceanic environment. This makes them unique compared to most of the well-known outflows of the Atlantic Ocean, and valuable "laboratories" for testing ideas about what controls the mixing and spreading of water masses formed in marginal seas.

OBJECTIVES

Our objectives are to:

1) Describe the synoptic-scale structure and variability of the Red Sea and Persian Gulf outflows where they enter the Indian Ocean, including water mass properties, equilibrium depth and spreading pathways.

2) Explore the dynamics of these two marginal sea outflows and compare to the better-known outflows of the Atlantic.

APPROACH

1) Collect all available AXBT and historical temperature-salinity data from NAVOCEANO's MOODS data archive for the Gulf of Aden and Gulf of Oman with the assistance of Mr. Bob Rushton, manager of the data archive.

2) Use the historical temperature-salinity data with the AXBT data to determine the properties and spreading pathways of the Red Sea and Persian Gulf outflows in the Gulf of Aden and Gulf of Oman, respectively.

3) Use the one-dimensional plume model of Price and Baringer (1994) to study the dynamics of these marginal sea outflows and compare with the Atlantic outflows.

WORK COMPLETED

This year we concentrated on an in-depth investigation of the dynamics of the Red Sea and Persian Gulf outflows using the Price and Baringer (1994) one-dimensional outflow model. The results were included in a manuscript that was re-submitted and accepted for publication in the Journal of Geophysical Research Oceans. We also produced a data report containing the quality-controlled hydrographic data from the Gulf of Aden and Gulf of Oman that had been acquired from the MOODS archive at NAVOCEANO. Our results were presented at the ONR-sponsored Arabian Marginal Seas and Gulfs Workshop in May, 1999 at Stennis Space Center.

RESULTS

Historical hydrographic data and a numerical plume model were used to investigate the initial transformation, dynamics and spreading pathways of Red Sea and Persian Gulf outflow waters where they enter the Indian Ocean. The annual mean transport of these outflows is relatively small (< 0.4 Sv), but they have a major impact on the hydrographic properties of the Indian Ocean at the thermocline level due to their high salinity. They are different from other outflows in that they flow over very shallow sills (depth < 200 m) into a highly stratified upper ocean environment, and they are located at relatively low latitudes (12°N and 26°N). Further, the Red Sea outflow exhibits strong seasonal variability in transport.

The four main results of this study are as follows. First, based on the observed T-S characteristics of the outflow source and product waters, we estimate that the Red Sea and Persian Gulf outflows are diluted by factors of about 2.5 and 4, respectively, as they descend from sill depth to their depth of neutral buoyancy (Figure 1). The high dilution factor for the Persian Gulf outflow results from the combined effects of large initial density difference between the outflow source water and oceanic water, and low outflow transport. Second, the combination of low latitude and low outflow transport (and associated low outflow thickness) results in Ekman numbers for both outflows that are O(1). This indicates that they should be thought of as frictional density currents modified by rotation, rather than geostrophic density currents modified by friction. Third, different mixing histories along the two channels that direct Red Sea outflow water into the open ocean result in product waters with significantly different densities, which probably contributes to the multi-layered structure of the Red Sea product waters. In both outflows, seasonal variations in source water and oceanic properties have some effect on the T-S of the product waters, but they have only a minor impact on equilibrium depth. Fourth, product waters from both outflows are advected away from the sill region in narrow boundary currents, at least during part of the year. At other times, the product water appears more in isolated patches.

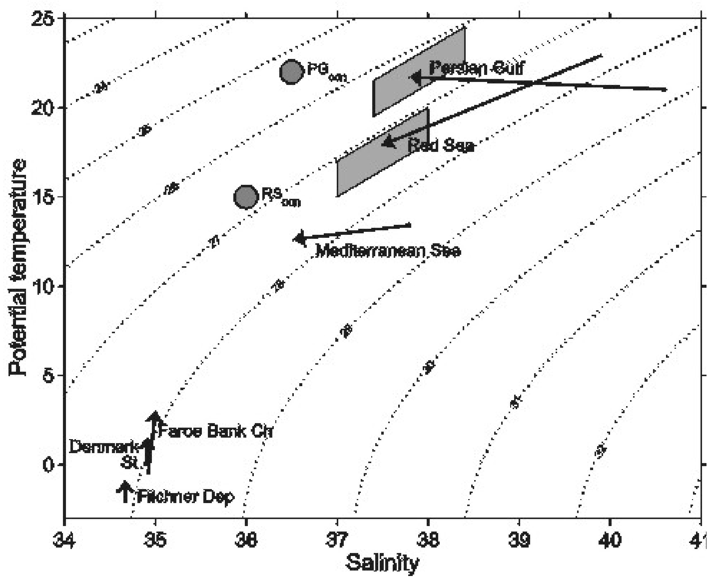

Figure 1: T-S diagram showing transformation of outflow water characteristics from source (arrow tail) to product (arrow head) for Red Sea outflow, Persian Gulf outflow and four other oceanic outflows. The source and product water properties were taken from Price and Baringer (1994) for the Weddell overflow from the Filchner Depression, Denmark Strait, Iceland Scotland Ridge and the Mediterranean overflows. The Red Sea and Persian Gulf source water properties represent winter conditions, and were taken from the NAVOCEANO hydrographic data and the Johns mooring, respectively. Product water properties were taken from the climatological water property distributions, and the oceanic values (shaded circles) represent means for the depth range over which the outflows descend. The shaded areas under the Red Sea and Persian Gulf arrow heads give an indication of the observed variability in product water T-S characteristics. The low- and mid-latitude overflow waters undergo much larger changes in density from source to product than do the high latitude overflows. The large changes in density arise mainly because the low- and mid-latitude overflows start at comparatively shallow depths of less than 300 m (sill depth), and at sites where there is a well-developed main thermocline. This results in the entrainment of oceanic water that is considerably less dense than the source water. The Red Sea product water characteristics lie about 60% of the distance between the source and oceanic end members, suggesting a 2.5-fold increase in outflow transport due to entrainment. For the Persian Gulf case, the product water characteristics are about 75% of the distance, indicating a 4-fold transport increase. The former is similar to the Mediterranean outflow, while the latter is significantly greater than for any of the Atlantic outflows.

IMPACT/APPLICATIONS

Our analysis has shown that the Gulf of Aden and Gulf of Oman are characterized by strong spatial and temporal variability of T-S properties due to the spreading of outflow waters. This has important implications for sound propagation in the area. Our data analysis and modeling efforts have shed light on the role of variations in the oceanic environment and topography on the characteristics of outflows.

TRANSITIONS

We continue to maintain an informal relationship and share results with NAVOCEANO through Mr. Jeff Kerling.

RELATED PROJECTS

We continue to discuss our results with Bill Johns, who is analyzing observations from the Bab-al-Mandeb and the Strait of Hormuz collected as part of an ONR-funded program. Some of these data were used in our outflow study. We have also interacted with Larry Pratt, who is studying hydraulic control in the Bab-al-Mandeb.

REFERENCES

Price, J. F., and M. O'Neil Baringer, 1994. Outflows and deep water production by marginal seas. *Progress in Oceanography*, **33**, 161-200.

PUBLICATIONS

Bower, A. S., H. D. Hunt and J. F. Price, 1999. The Character and Dynamics of the Red Sea and Persian Gulf Outflows. *Journal of Geophysical Research*, in press.

Alessi, C. A., H. D. Hunt and A. S. Bower, 1999. Hydrographic Data from the US Naval Oceanographic Office: Persian Gulf, Southern Red Sea and Arabian Sea 1923-1996. *Woods Hole Oceanographic Institution Technical Report WHOI-99-02*, 22 pp. + appendices.